Neutrino mass, $0\nu\beta\beta$ signature in doublet left-right symmetric theories and its cosmological implications

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Overview of the talk

- Introduction to LRSM
- Model : Doublet variant LRSM
- Neutrino mass generation
- Gauge Coupling Unification
- Neutrinoless Double Beta Decay ($0\nu\beta\beta$)
- Cosmological Implications
- LRSM without scalar bidoublet
- Summary

Why Left-Right symmetric theories?

- Theoretical predictions of Standard Model (SM) really match well with collider findings.
- Though some theoretical and observational inconsistencies persist as
  - Explanation of origin and smallness of neutrino mass pointed out by recent neutrino oscillation experiments (Fukuda et al.'2001).
  - Parity violation in low-energy weak interaction while other fundamental interactions are parity conserving.
- SM can be thought as low-energy effective field theory of some high energy parity conserving framework $\Rightarrow$ Left-Right Symmetric theories (LRSMs) (Pati et al.'74, Mohapatra et al.'75 and so on).
- Bonus : It naturally introduces Right Handed Neutrinos (RHNs) $\Rightarrow$ in-built seesaw generation of neutrino mass.

Doublet variant LRSM : Model (Perez et al.'2016)

- Gauge group : $\mathcal{G}_{LR} \equiv SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$.
- Fermions :
$$q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3,2,1,1/3), \quad q_R \equiv \begin{pmatrix} u_R \\ d_R \end{pmatrix} = (3,1,2,1/3),$$
$$\ell_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1,2,1,-1), \quad \ell_R \equiv \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} = (1,1,2,-1).$$
- Scalars :
$$\Phi \equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} = (1,2,2,0), \quad H_L \equiv \begin{pmatrix} h_L^+ \\ h_L^0 \end{pmatrix} = (1,2,1,1),$$
$$H_R \equiv \begin{pmatrix} h_R^+ \\ h_R^0 \end{pmatrix} = (1,1,2,1), \quad \delta^+ = (1,1,1,2).$$
- Electric charge assignment : $Q = T_{3L} + T_{3R} + \frac{B-L}{2}$.

Neutrino mass generation

$$\mathcal{L}_{\text{Yuk}} = \bar{q}_L \left(Y^q \Phi + \tilde{Y}^q \tilde{\Phi} \right) q_R + \bar{\ell}_L \left(Y^\ell \Phi + \tilde{Y}^\ell \tilde{\Phi} \right) \ell_R + \lambda^L \ell_L^T C \ell_L \delta^+ + \lambda^R \ell_R^T C \ell_R \delta^+ + \text{h.c.} \quad (1)$$

- VEV assignment :

$$\langle \Phi \rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 \end{pmatrix}, \langle H_L \rangle = \begin{pmatrix} 0 \\ v_L \end{pmatrix}, \langle H_R \rangle = \begin{pmatrix} 0 \\ v_R \end{pmatrix}, \langle \delta^+ \rangle = 0.$$

- At tree level, no Majorana mass generation for neutrinos in this framework.
- After spontaneous symmetry breaking (SSB)

$$\mathcal{G}_{LR} \xrightarrow{\langle H_R \rangle} \mathcal{G}_{SM} \xrightarrow{\langle H_L \rangle, \langle \Phi \rangle} U(1)_Q \times SU(3)_C \quad (2)$$

we have Dirac type masses for charged and neutral fermions as

$$M_u = Y^q v_1 + \tilde{Y}^q v_2^*, \quad M_d = Y^q v_2 + \tilde{Y}^q v_1^*$$

$$M_D = Y^\ell v_1 + \tilde{Y}^\ell v_2^*, \quad M_e = Y^\ell v_2 + \tilde{Y}^\ell v_1^*$$

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- Now in scalar potential we have quartic coupling $\mathcal{V} \supset \lambda' H_L^\dagger \Phi H_R^* \delta^+$.

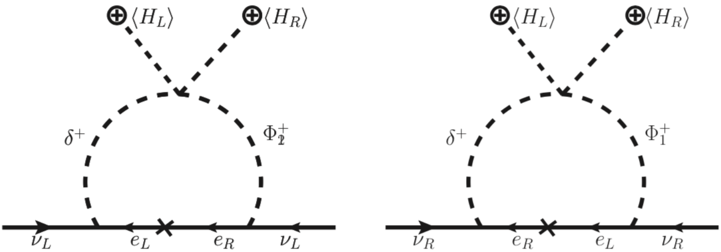

Figure: Radiative Majorana mass generation at one-loop level

- Loop-induced Majorana mass :

$$M_{L,R}^{\text{1-loop}} = \frac{\lambda' \langle H_L \rangle \langle H_R \rangle}{16\pi^2} \frac{\lambda^{L,R} M_\ell Y_\ell^T}{M^2} \mathcal{I}$$

with $M = \max(M_{\delta^+}, M_\Phi)$.

Continued ...

- Here loop factor $\mathcal{I} = \frac{\log\left[\frac{M_\ell^2}{M_{\delta+}^2}\right] M_{\delta+}^2}{M_{\delta+}^2 - M_\ell^2} - \frac{\log\left[\frac{M_\ell^2}{M_\Phi^2}\right] M_\Phi^2}{M_\Phi^2 - M_\ell^2}$.
- Complete neutral lepton mass matrix becomes,

$$\mathcal{M} = \begin{pmatrix} M_L^{\text{1-loop}} & M_D \\ M_D^T & M_R^{\text{1-loop}} \end{pmatrix}$$

In the mass hierarchy limit $M_R^{\text{1-loop}} \gg M_D \gg M_L^{\text{1-loop}}$, we can use seesaw approximation (with the limit $M_L^{\text{1-loop}} \to 0$) to find the light and heavy neutrino mass eigenvalues,

$$\boxed{m_\nu = -M_D (M_R^{\text{1-loop}})^{-1} M_D^T, \qquad m_R = M_R^{\text{1-loop}}}$$

Gauge-Coupling Unification

- One-loop RG equation (DRT Jones'82) for tracing the running gauge couplings g_i:

$$\mu \frac{\partial g_i}{\partial \mu} = \frac{b_i}{16\pi^2} g_i^3$$

  where μ is the desired energy scale.

- One-loop beta coefficients

$$b_i = -\frac{11}{3}\mathcal{C}_2(G) + \frac{2}{3}\sum_{R_f} T(R_f)\prod_{j\neq i} d_j(R_f) + \frac{1}{3}\sum_{R_s} T(R_s)\prod_{j\neq i} d_j(R_s) \tag{3}$$

  where $\mathcal{C}_2(G)$ is the quadratic Casimir operators for gauge bosons, $T(R_{f,s})$ are the traces of the irreducible representation $R_{f,s}$ for a given fermion or scalar and $d(R_{f,s})$ is the dimension of the representation.

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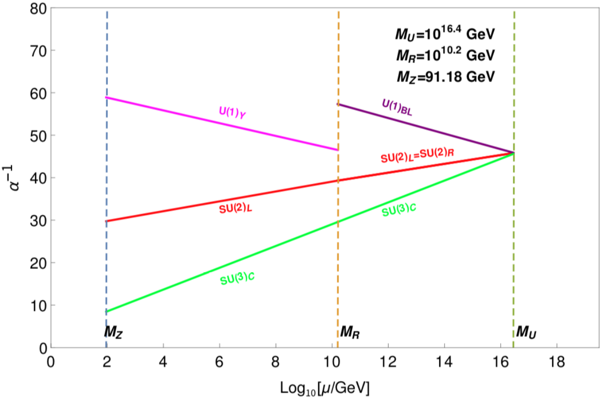

Figure: With particle content discussed previously, we have achieved successful unification at $M_U = 10^{16.4}$ GeV with LR breaking scale $M_R = 10^{10.2}$ GeV.

- M_R scale is very high, impossible to see it in recent day colliders.

Low-Scale M_R with successful unification

- Cost : Have to extend the particle spectrum by adding $\xi(6, 1, 1, 4/3)$ and another 3 copies of δ^+.

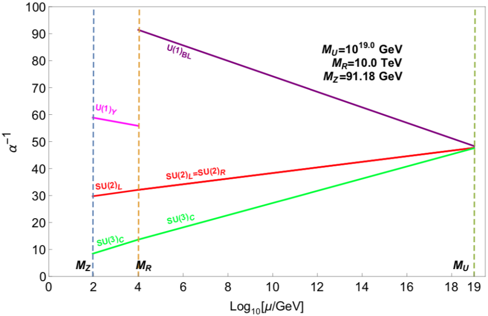

Figure: Expanding particle spectrum we can have successful unification with low-scale $M_R = 10$ TeV.

- Now we can expect rich phenomenology from this TeV scale LR-breaking framework.

Benchmark values for neutrino masses

- Here we use $\langle\Phi\rangle \sim v_1 = 170$ GeV, $\langle H_L\rangle = v_L = 34$ GeV, $M_{\delta^+} \sim$ TeV.

λ'	λ^R	Y^ℓ	$M_R^{\text{1-loop}}$(keV)	M_D(eV)	M_ν(eV)
10^{-2}	10^{-3}	5.86×10^{-11}	12.67	0.1	10^{-6}
1	0.5	5.86×10^{-12}	6.3	0.1	1.59×10^{-6}
1	0.5	4.63×10^{-10}	1000	10	10^{-4}
10^{-2}	10^{-3}	5.86×10^{-10}	126.7	1	10^{-4}

Table: Estimated values of physical masses for light and heavy neutrinos using derived values of M_D and radiatively generated $M_{L,R}^{1-\text{loop}}$ using representative set of input model parameters.

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

- $0\nu\beta\beta$ is a decay mode of a given isotope where two neutrons simultaneously convert into two protons and two electrons without accompanying any external neutrinos (Mohapatra et al.'81, Hirsch et al.'96).
- Experimental observation of such rare process $\Rightarrow$ Confirmation of Majorana nature of neutrinos indicating Lepton Number Violation (LNV) processes (Majorana'37).

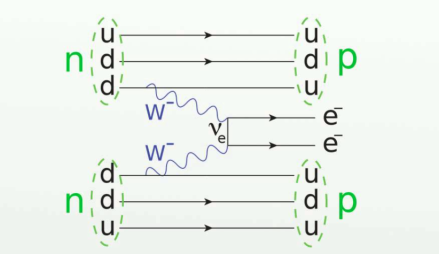

Figure: Generic Feynman diagram for $0\nu\beta\beta$ process (Picture Courtesy : Wikipedia)

Flavor and Mass eigenstates of neutrinos

- With $\nu_\alpha \equiv \nu_{L\alpha}$ and $N_\beta \equiv \nu_{R\beta}$,

$$\boxed{\nu_\alpha = U_{\alpha i}\nu_i + S_{\alpha i}N_i, \quad N_\beta = T_{\beta i}\nu_i + V_{\beta i}N_i}$$

- Here the mixing matrices can be designated as,

$$\begin{pmatrix} U & S \\ T & V \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2}RR^\dagger & R \\ -R^\dagger & 1 - \frac{1}{2}R^\dagger R \end{pmatrix} \begin{pmatrix} U_\nu & 0 \\ 0 & U_N \end{pmatrix}$$

  with U_ν and U_N are diagonalising matrices of light and heavy neutrino mass matrices m_ν and m_R respectively.
- Light-heavy neutrino mixing $R = M_D(M_R^{\text{1-loop}})^{-1}$.

Various Contributions to $0\nu\beta\beta$

- Contributing channels to $0\nu\beta\beta$ in this framework,
  - Exchange of light and heavy neutrinos via purely left-handed currents ($W_L - W_L$ mediation).
  - Exchange of light and heavy neutrinos via purely right-handed currents ($W_R - W_R$ mediation).
  - Mixed helicity λ diagrams involving ν_i, N_i mixing.
  - Mixed helicity η diagrams involving ν_i, N_i mixing and $W_L - W_R$ mixing.
- Half-life coming from these contributions,

$$\frac{1}{T_{1/2}^{0\nu}} = G_{01}\left(|\mathcal{M}_\nu \eta_\nu^L + \mathcal{M}'_N \eta_N^L|^2 + |\mathcal{M}'_N \eta_N^R + \mathcal{M}_\nu \eta_\nu^R|^2 + |\mathcal{M}'_\lambda(\eta_\lambda^\nu + \eta_\lambda^N) + \mathcal{M}'_\eta(\eta_\eta^\nu + \eta_\eta^N)|^2\right) \tag{4}$$

- Here G_{01} represents standard $0\nu\beta\beta$ phase space factor, $\mathcal{M}_i$ represent nuclear matrix elements for various exchange processes and η_i are particle physics parameters.

Particle Physics parameters

- Left-handed current effects :
  - $\eta_{\nu}^{L} = \frac{1}{m_e} \sum_{i=1}^{3} U_{ei}^{2} m_i$.
  - $\eta_{N}^{L} = \frac{1}{m_e} \sum_{i=1}^{3} S_{ei}^{2} M_i$.
- Right-handed current effects :
  - $\eta_{N}^{R} = \frac{1}{m_e} \left(\frac{g_R}{g_L}\right)^4 \left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \sum_{i=1}^{3} V_{ei}^{*2} M_i$.
  - $\eta_{\nu}^{R} = \frac{1}{m_e} \left(\frac{g_R}{g_L}\right)^4 \left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \sum_{i=1}^{3} T_{ei}^{*2} m_i$.
- Mixed current effects :
  - λ diagrams : $\eta_{\lambda}^{\nu} = \left(\frac{g_R}{g_L}\right)^2 \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sum_i U_{ei} T_{ei}^{*} \sim \frac{1}{|p|}$
  - η diagrams : $\eta_{\eta}^{\nu} = \left(\frac{g_R}{g_L}\right) \tan\xi \sum_i U_{ei} T_{ei}^{*}$

Numerical Results

- For $M_R \sim 10^{10}$ GeV, new gauge boson masses $\sim M_R$ scale $\Rightarrow$ far away from LHC reach.
  - Ratio $\frac{M_{W_L}}{M_{W_R}}$ and $W_L - W_R$ mixing i.e., tanξ negligible.
  - No new physics contributions to $0\nu\beta\beta$ from RH currents and mixed helicity channels.
  - Due to negligible light-heavy mixing $\frac{M_D}{M_R^{\text{1-loop}}} \Rightarrow$ Negligible contributions from LH currents.
- For $M_R \sim 10$ TeV, M_{W_R}, M_{Z_R} ∼few TeV, can give interesting collider phenomenology.
  - RH and mixed helicity contributions are comparatively larger here.
  - Also LH current effects are also giving significant contribution.
  - New physics contributions are indeed large enough to saturate current experimental bounds i.e., GERDA (Agostini et al.'2013), KamLAND-Zen (Gando et al.'2013) etc.

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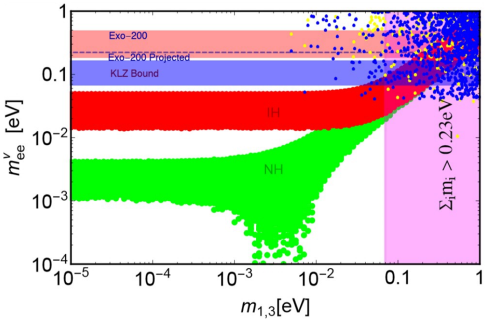

Figure: Plots for effective Majorana mass parameters

- Green and Red bands come from standard $W_L - W_L$ contribution to $0\nu\beta\beta$.
- Vertical pink band corresponds to excluded region from cosmology data (PAR Ade et al.'2014).
- Blue and Yellow dots are coming from η and λ diagrams.

Cosmological Implications

- We have keV-MeV scale RHNs within this framework.
- Such light sterile neutrino can be considered as warm dark matter (WDM), also they can work as cold DM ensuring the large scale structure formation (Pagels et al.'85, Peebles'82).
- If $M_R \sim$ few TeV i.e., not far above the EW breaking scale, due to presence of extra gauge interaction, such RHNs can play role of DM having a similar relic density as one of the light neutrinos (Linder et al.'2010, Senjanovic et al.'2012).
- Various cosmological and astrophysical bounds can be summarised as,

Constraints	M_R^{1-loop}	τ_N	M_{W_R}
Dwarf Galaxy	$\gtrsim 0.4 - 0.5$ keV	–	–
Lyman-α	$\gtrsim 0.5 - 1$ keV	–	–
BBN and CMB	–	$\lesssim 1.5$ sec	–
$0\nu\beta\beta$	–	–	$\gtrsim 6 - 8$ TeV

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- Problem : keV scale RHN with right-handed gauge boson mass around few TeV can create overabundance of DM (Linder et al.'2010).
- Only way out : to dilute the number density of lightmost RHN say, N_1 by so-called late entropy production mechanism.
- Such late decay should involve some heavier RHN which will decay to some relativistic SM particle which can quickly come to equilibrium with cosmic plasma.
- Due to dilution mechanism to work $\Rightarrow N_1$ cannot be a decay product of heavy RHNs i.e., $N_{2,3}$.
- $N_{2,3}$ will work as diluters here.

Some facts about such dilution mechanism and DM

- In order to achieve sizeable dilution $m_{N_{2,3}}$ should not exceed its freeze-out temperature T_f.
- Depending upon diluters' mass two decay channels are possible :
  - $N_{2,3} \to \ell jj$
  - $N_{2,3} \to \ell\pi$.
- The produced lepton can be either e or μ.
- In our analysis, light-heavy neutrino mixing $\lesssim 10^{-5} \Rightarrow$ forbids LH neutrino oscillation back to RHNs, thereby forbids overabundance problem.
- But this tiny mixing cause two decay channels to be prominant :
  - $N_1 \to \nu\gamma$
  - $N_1 \to 3\nu$.
- Such RHNs easily satisfy stability criteria to qualify as WDM.

LRSM without scalar bidoublet

- Now we consider LRSM framework with usual "LRSM" fermion doublets, scalar doublets $H_{L,R}$, but no bidoublet.
- In order to have Dirac masses for quarks and charged leptons, we have introduced vector like fermions (Davidson et al.'87).

$$U_{L,R} = (3,1,1,4/3), \quad D_{L,R} = (3,1,1,-2/3), \quad E_{L,R} = (1,1,1,-2).$$

- After SSB, we have Dirac masses for fermions as,

$$M_{uU} = \begin{pmatrix} 0 & \lambda_U^L v_L \\ \lambda_U^R v_R & M_U \end{pmatrix}, \quad M_{dD} = \begin{pmatrix} 0 & \lambda_D^L v_L \\ \lambda_D^R v_R & M_D \end{pmatrix}$$
$$M_{eE} = \begin{pmatrix} 0 & \lambda_E^L v_L \\ \lambda_E^R v_R & M_E \end{pmatrix}, \quad M_{\nu N} = \begin{pmatrix} 0 & \lambda_N^L v_L \\ \lambda_N^R v_R & M_N \end{pmatrix}$$

- No LNV in this framework.

Accomodating LNV in LRSM without bidoublet

- To accomodate LNV, we have to extend scalar sector with $SU(2)_{L,R}$ triplets $\Delta_{L,R}$.
- Scalar Potential,

$$\mathcal{V}(H_L, H_R, \Delta_L, \Delta_R) \supset -\mu_1^2(H_L^\dagger H_L) - \mu_2^2(H_R^\dagger H_R) + \mu_3^2 \text{Tr}(\Delta_L^\dagger \Delta_L) + \mu_4^2 \text{Tr}(\Delta_R^\dagger \Delta_R) \quad (5)$$

- Note the sign of $\mu^2_{1,2,3,4}$ in the scalar potential.
- Minimisation condition allows non-zero VEVs for doublets but no VEVs from triplets.
- After acquiring VEVs by doublets, VEV for triplets will be induced by trilinear coupling $\mu(H_L^T i\sigma_2 \Delta_L H_L + H_R^T i\sigma_2 \Delta_R H_R)$.
- Idea : To break LRSM with doublets and induce small VEVs for triplets such that we can get light RHN masses and their implications to $0\nu\beta\beta$.

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- Majorana masses for light neutrinos are given by $m_\nu = f u_L$ and for heavy neutrinos as $M_R = f u_R$.
- Here $u_{L,R}$ correspond to VEVs of scalar triplets.

Summary

- LRSM is a BSM framework to explain both parity violation in weak interaction and origin of small neutrino mass.
- Doublet variant LRSM with extra charged singlet can explain radiately generated Majorana mass for neutrinos.
- Such framework can be embedded in non-SUSY $SO(10)$ GUT scenario.
- This model can give rise to significant new physics contribution to $0\nu\beta\beta$ which can satisfy various recent experimental bounds.
- keV-MeV scale RHNs can qualify as warm dark matter in the universe with proper stability criterion.
- We can also generate neutrino masses within doublet LRSM without scalar bidoublet by expanding the fermion sector with vector like fermions.


Thank
you!!